SDM Enabled Record Field Trial Achieving 300+ Tbps Trans-Atlantic Transmission Capacity

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Abstract: A per fiber-pair real-time capacity of 25.6 Tbps is demonstrated with 0.5 dB Q-factor commissioning margin across 6611 km of SDM enabled trans-Atlantic link aggregating to a record 307.2 Tbps on a single submarine cable.

1. Introduction

Submarine communication systems are an essential technology to ensure global internet connectivity. As capacity requirements continue to grow owing to increased device connectivity and higher bandwidth applications, there is a need to grow the data throughput of submarine networks to meet these ever-increasing demands. To this end, the number of commissioned submarine cables has systematically grown in the past decade with 2021 alone witnessing 26 new "ready for service" cables [1]. While laying more submarine cables can help meet the capacity demands, it is an expensive and time-consuming process. Therefore, it is often preferred to extract additional capacity out of an existing cable before laying a new one. Unfortunately, we are approaching the limits of transceiver technologies for extracting any more capacity out of individual fiber pairs (FP) within a submarine cable [2].

One of the greatest challenges of submarine cables is the amount of electrical power that can be delivered to these cables to power its optical repeaters [3]. This limitation has hindered our ability to introduce additional repeaters in the cable thereby limiting the number of FPs and overall cable capacity. Recently, it was demonstrated that it is possible to share the repeater gain across various FPs in a submarine cable through a technology known as pump-sharing [4]. The lower gain forces the FP to operate in the linear regime of the nonlinear Shannon limit [5] thereby reducing the operational gap to capacity, achieving higher total cable capacity, and reducing the cost per unit capacity. This is known as space division multiplexing (SDM) in submarine cables.

Here, we present our field trial results on the world's first SDM submarine cable – Dunant. Using real-time payload traffic, we demonstrate deployable capacities of 25.6 Tbps (256x100 GbE ethernet clients) per FP with 0.5 dB Q margins aggregating to a record trans-Atlantic transmission of 307.2 Tbps (3072x100 GbE ethernet clients) on the cable. Our discussions include a comparison to our previous field trial on Marea, which is widely regarded as the highest performing non-SDM submarine cable [6]. Additionally, we present our results on a loop-back link that emulates an equivalent trans-Pacific system.

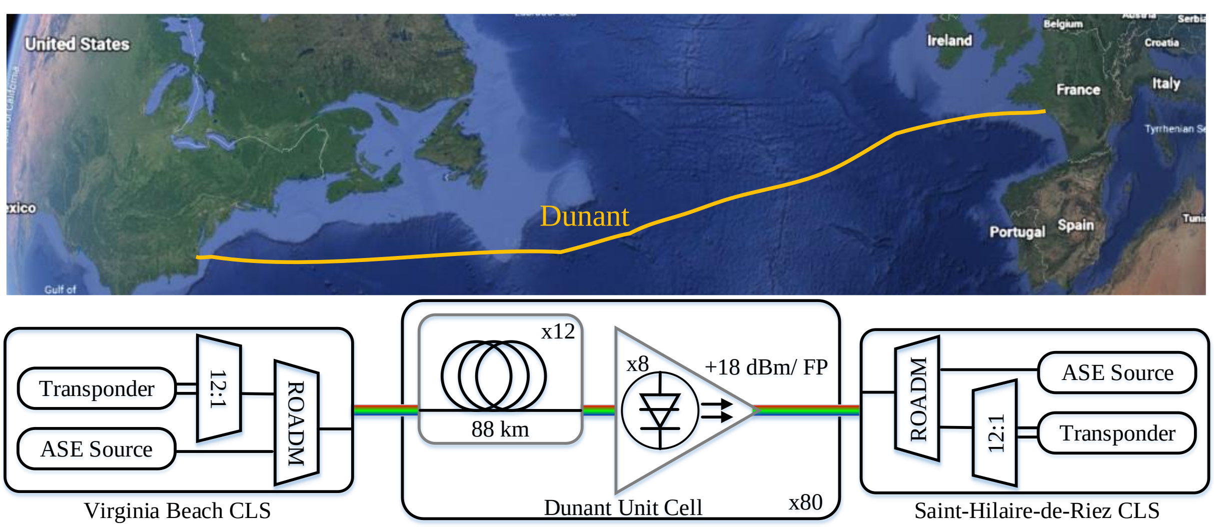

Fig. 1: Simplified schematic diagram of the field trial setup. Dunant cable shares the repeater gain from 8 optical pumps between its 12 FPs using pump sharing technology resulting in a reduced optical output power of +18 dBm/FP. A loop-back was used at Saint-Hilaire-de-Riez to emulate an equivalent trans-Pacific cable.

2. Experimental Setup

The bidirectional field trial setup was based at two locations - Virginia Beach (VB), USA cable landing station (CLS) and Saint-Hilaire-de-Riez (FR), France CLS, Fig. 1. Both sites were equipped with a finely tunable, dual wavelength, multi-symbol rate 800 Gbps transceiver [7] which is connected to a 12:1 colourless multiplexer/demultiplexer. This output is combined with an ASE source and fed into a wavelength-selective-switch (WSS) based ROADM that couples into Dunant's wetplant. The ASE source provides spectral occupancy for constant power submarine repeaters and emulates the effects of neighboring channels. Additionally, the ASE source was used to measure the link signal to noise ratio (SNR) using channelized 50 GHz ASE spectra.

Dunant uses 8 optical pumps in its repeaters with the optical power shared between the 12 FPs. The total optical output power is +18 dBm/FP, which is approximately 1.76 dB (factor of 1.5) lower compared to equivalent non-SDM submarine cables [8]. Each FP consists of 80 spans, with the majority measuring 88 km in length (~13.8dB) and using 125 μm^2 effective area fiber. Dunant is 6611 km long.

The Infinera CHM6S transceivers used in the trial (one per end) employ an indium phosphide (InP) photonic integrated circuit (PIC) with accompanying analogue electronics and DSP. Each of the two wavelengths per CHM6S module consists of 8 subcarriers and employs probabilistically shaped constellations with long code words to achieve high performance. To calculate the performance of various information rates (IRs) and spectral efficiencies (SE) on the cable, the transceiver was tuned across the spectra while configuring ASE noise around these carriers. Various DSP parameters were tuned across the cable spectra to obtain best performance across the cable [6]. Additionally, the carrier and local ASE launch power (LP) was varied to understand its impact on the Q-factor.

3. Results

The measured SNR for the Dunant FP under test varied from ~15 dB in the red end to ~13 dB in the blue end, as shown in Fig. 1(a). The SNR is consistently lower than that of Marea (blue crosses) owing to lower repeater output power and higher span lengths [8]. Figure 1(b) shows the performance of a 400 Gbps signal operating at 8 bits per second (BPS) SE for varying launch powers. The performance eventually starts to degrade in the red with increasing LP, while in the blue the performance of the signal monotonically increases with LP. This demonstrates that the cable is operating at different regimes of the nonlinear Shannon limit within the repeater bandwidth. Owing to these characteristics, one needs to be careful when estimating fiber capacities and channel plans for an SDM cable. Performance of a channel at the peak of the Q vs LP curve cannot be used as the fiber pair does not have sufficient repeater output power to operate all the channels at peak signal quality. Therefore, we begin estimating capacities using the performance of our signals at flat launch (0 dB), Fig. 1(c). Our investigated signals include 400 Gbps at 8 BPS, 450 Gbps at 7.875 BPS, 500Gbps at 7.5 BPS and 400 Gbps at 7.5 BPS. As expected, the Q-factor decreases

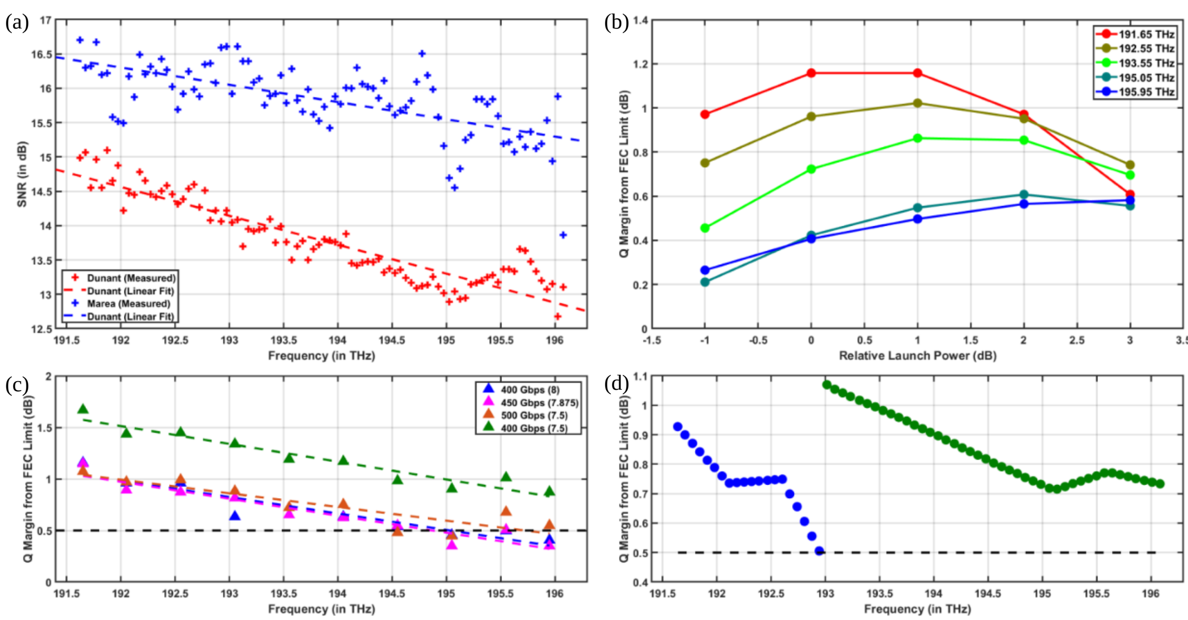

Fig. 2: Various performance metrics of Dunant as obtained during the field trial. (a) SNR variation across repeater bandwidth for Dunant and Marea. (b) Q-factor vs launch power delta (from flat PSD) for 400 Gbps 8 BPS signal at various frequencies across the repeater bandwidth. (c) Performance of signals with various IRs and SEs across Dunant's repeater bandwidth. BPS is denoted within parentheses in the legend. Black dashed line represents 0.5 dB Q factor margin from FEC limit. (d) Extrapolated deployable channel plan and its associated Q factor margins for a maximum capacity of 25.2 Tbps/FP at 0 dB launch power delta. Figures (c) and (d) use the same color scheme for its signals.

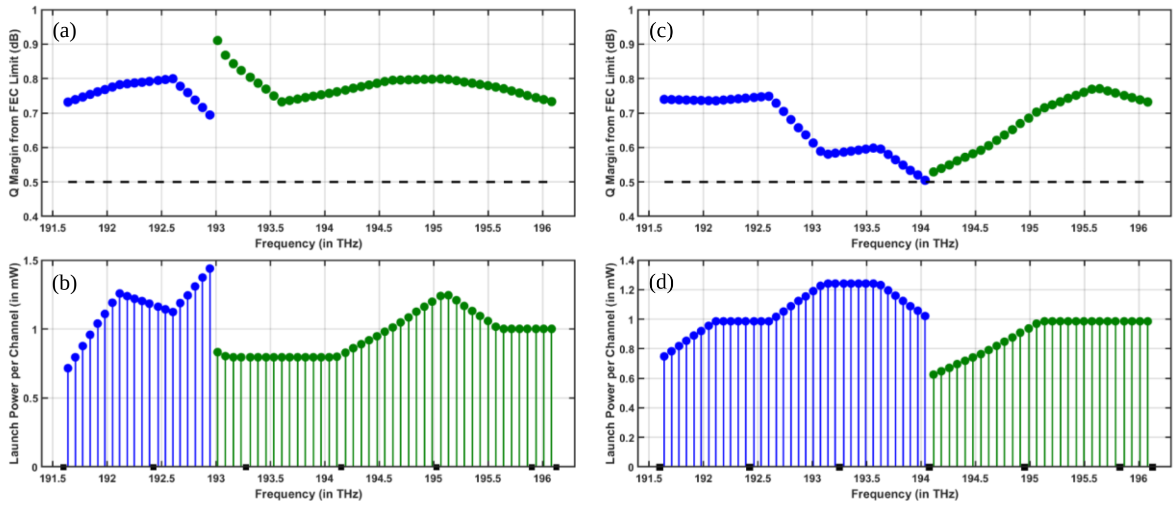

Fig. 3: Extrapolated channel plan along with its associated Q-factor margins and channel launch power after power sharing for (a-b) maximum margin and (c-d) maximum capacity. Black squares in (b) and (d) represent WSS guard bands.

with increasing carrier frequency which is consistent with the measured SNR profile. The Q-factor also decreases with increasing SE consistent with Shannon's theory [5]. The commissioning margin was set to 0.5 dB in Q-factor from the FEC limit for our capacity estimates. We initially calculated a total capacity of 25.2 Tbps/FP using 20x400 Gbps (8 BPS) and 43x400 Gbps (7.5 BPS) signals, Fig. 1(d). Note that the reported data rate is consistent with 100 GbE ethernet client rates and the actual signals have >100Gb/s line rates. Moreover, the channel plan accounts for wavelocker and WSS port guardbands which are consistent with deployment constraints and ITU-T 12.5 GHz grid.

Operating in the linear regime of the nonlinear Shannon limit in an SDM cable allows one to "power-share" with high flexibility when designing channel plans. Optical power can be 'borrowed' from a channel operating at high Q-factor and 'given' to channels operating at low Q-factors to maximize deployment margins or capacity, Fig. 3. There is limited flexibility to power-sharing in non-SDM cables as all channels operate near the peak of the Q vs LP curve and changing the LP in either direction reduces the Q-factor. For Dunant, power redistribution allowed us either to increase the worst-case operating margin to 0.7 dB Q-factor for the previous channel plan, Fig. 3(a-b) or increase the maximum capacity to 25.6 Tbps/FP using 36x400 Gbps (8 BPS) and 28x400 Gbps (7.5 BPS) signals in Fig. 3(c-d).

Using the same deployment constraints and 0.5 dB Q-factor commissioning margin as Dunant, we achieved 27.8 Tbps/FP on Marea in our previous field trial [6]. While Marea has a 2.1 Tbps advantage in capacity over Dunant on each FP, Dunant aggregates a staggering 307.2 Tbps over its 12 FPs as compared to 222.4 Tbps on Marea over its 8 FPs. This represents a capacity gain 38.1% using SDM with 12 FPs and 8 repeater pumps.

Finally, we measured the performance of Marea and Dunant in a loop back setup to quantify the benefits of SDM cables over equivalent trans-pacific submarine systems. Using the same deployment constraints as previously discussed, we obtained 17.7 Tbps/FP on Dunant and 19.8 Tbps/FP on Marea aggregating to 212.4 Tbps and 158.4 Tbps cable capacities respectively and demonstrating a 34.1% capacity gain using SDM.

4. Conclusions

We report results from our field trial on the first ever trans-Atlantic SDM submarine cable - Dunant. Using Infinera's InP based transceiver, we achieved a capacity of 25.6 Tbps/FP having worst-case 0.5 dB Q margin. This aggregates to 307.2 Tbps over the submarine cable. To the best of our knowledge, this is the highest real-time 100 GbE ethernet based deployable cable capacity demonstrated over any trans-Atlantic submarine cable. Additionally, the results were compared to deployable cable capacity on Marea and >34% capacity improvements were shown.

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